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ENCLOSURE FIRE DYNAMICS MODEL

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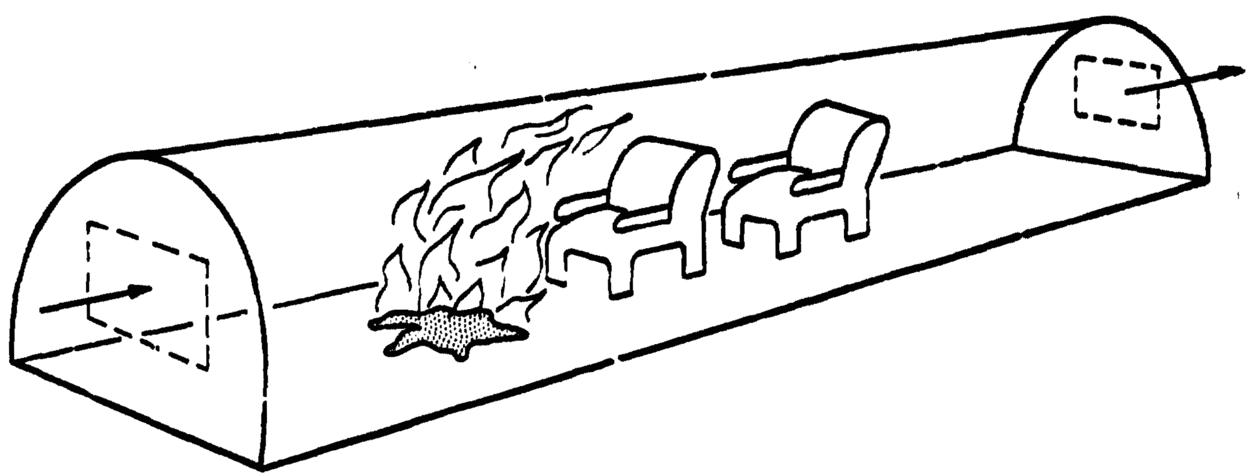
ENCLOSURE FIRE DYNAMICS MODEL

PLAN OF THE PRESENTATION

1) PRACTICAL SITUATION. WHY A FIRE DYNAMICS MODEL?
2) DIFFICULTIES IN ESTABLISHING A MODEL.
3) BRIEF REVIEW OF ENCLOSURE-FIRE MODELS AVAILABLE.
4) OUR APPROXIMATION OF THE PRACTICAL SITUATION.
5) OUR MODEL.

PRACTICAL SITUATION



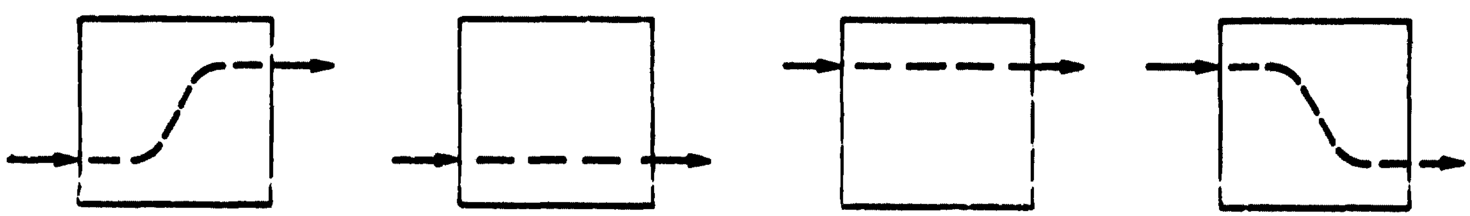
IT HAS BEEN SHOWN BY GLOBAL MODELING OF EXPERIMENTAL DATA THAT FIRE CAN BE LIMITED IN ITS PROPAGATION BY TWO FACTORS:

- LACK OF O_2 (VENTILATION, ENCLOSURE VOLUME)
- LACK OF FUEL (FUEL LOAD, FUEL SURFACE)

PRACTICAL SITUATION
(contd)

IT HAS ADDITIONALLY BEEN OBSERVED THAT:

- THE OUTCOME OF THE FIRE IS STRONGLY INFLUENCED BY VENTILATION PATTERNS



- THE OUTCOME OF THE FIRE IS STRONGLY INFLUENCED BY THE LOCATION OF THE FIRE
- THERE IS A STRONG TEMPERATURE CHANGE NOT ONLY IN THE HORIZONTAL, BUT ALSO IN THE VERTICAL DIRECTION DUE TO AIR BUOYANCY
- SURFACES, OTHER THAN THOSE BURNING, ARE FURTHER IGNITED DUE TO RADIATION AND/OR CONVECTION FROM THE EXISTING FIRE

GLOBAL MODELING CANNOT PREDICT THESE LATTER FIRE CHARACTERISTICS

→ A DETAILED ANALYTICAL MODEL IS NEEDED

DIFFICULTIES IN ESTABLISHING A MATHEMATICAL MODEL DESCRIBING FIRE IN AIRCRAFT

1) Geometrical aspects
2) Turbulent aspects

   Lack of data to indicate levels of turbulence transport (cm^2/sec)
3) Combustion aspects

   Lack of knowledge on the detailed chemical mechanism. Lack of data (E and A) to approximate those mechanisms by a one step reaction.
4) Description of the coupling between combustion and turbulence
5) Radiation aspects

   View factors, emissivities, gas phase absorptance and transmittance
6) Boundary conditions and wall effects

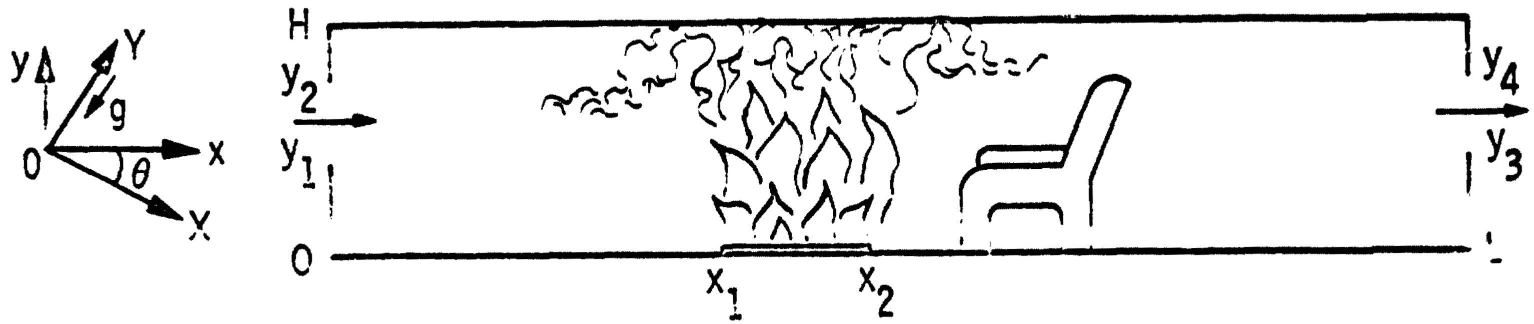
   Difficult to correctly approximate both wall and core phenomena within reasonable constraints (money, time, computer time)
7) Lack of thermophysical and thermochemical constants for various materials that are used in aircraft.

REVIEW OF ENCLOSURE — FIRE MODELS

	FIELD OR ZONE	CONSERVATION EQUATIONS: MASS	MOM	ENERGY	GAS SPECIE	SMOKE	SURFACE IGNITION	COMBUSTION OF GASES	TURBULENCE	BOUNDARY CONDITIONS: VENTILATION: NATURAL OR FORCED	NO. OPENINGS	SURFACES	RADIATION	PLUME MODEL	SPECIFIC DATA REQUIRED	PREDICTED QUANTITIES: P	T_g	T_s	$\bar{V}$	SMOKE	SPECIES
EFDM	F (2-D)	✓	✓	✓	✓	LATER	LATER	P	EFFECTIVE TRANSPORT PROPERTIES	F/N	2	NO-SLIP VELOCITY; HEAT TRANSFER TO SURFACES; GASIFICATION OF FUEL	✓	N/A	THERMOPHYSICAL AND THERMOCHEMICAL PROPERTIES, STOICHIOMETRY	✓	✓	✓	✓	LATER	✓
NOTRE DAME	F (2-D)	✓	✓	✓					ALGEBRAIC MODEL (CORE AND WALL)	N	1,2	NO-SLIP VELOCITY; HEAT TRANSFER TO SURFACES	1-D MODEL: SOOT, H_2O, CO_2 BANDS	N/A	VARIOUS FUNDAMENTAL PHYSICAL PROPERTIES; SPECIE AND SOOT CONCENTRATION	✓	✓	?	✓		
Mc DONNELL DOUGLAS	Z (3)	✓		✓	UK		UK	SE		UK	UK	HEAT TRANSFER TO SURFACES	BLACK BODY?		UK		✓	✓			UK
DAYTON	Z (3)	✓-E	PLUME, CEILING JET ONLY	✓-E	✓-E	✓-E	✓-E	E		F/N	2	HEAT TRANSFER TO WALLS AND CEILING	ABSORBING AND EMITTING UPPER LAYER: FLAME RADIATION MODEL INCLUDING SOOT	FANG/ROCKET FLAME/PLUME MODEL; STEWARD MODEL IN BUOYANT PLUME	RATES AND TIMES GOVERNING TRANSITION STATES: HEAT RELEASE, SPECIE EVOLUTION, FLAME SPREAD		✓	✓		✓	O_2, CO, HCN, HCl, SO_2, HF
IITRI	Z (2)	✓-E		✓-E			✓-E	E		N	1	HEAT TRANSFER TO WALLS AND CEILING	BLACK BODY?	FANG's FLAME/PLUME MODEL	FUEL GASIFICATION RATES; COMBUSTION EFFICIENCY		✓	✓			
NBS	Z (4)	✓		✓				P		N	1	HEAT TRANSFER TO WALLS AND CEILING		STEWARD'S "TURBULENT DIFFUSION BUOYANT FLAME" MODEL	SOOT CONCENTRATION ΔH, GASIFICATION TEMPS, STOICHIOMETRY						
HARVARD	Z (2)	✓-E		✓-E				E		N	1	HEAT TRANSFER TO UPPER WALLS AND CEILING	?	MORTON'S "POINT-SOURCE" BUOYANT PLUME	BURNING RATES		✓	✓			

E - EMPIRICAL INPUT REQUIRED
SE - SEMI-EMPIRICAL
P - PREDICTED
NA - NOT APPLICABLE
UK - UNKNOWN

APPROXIMATION OF THE PRACTICAL SITUATION



MATHEMATICAL MODELING INCLUDES:

- WRITING THE CONSERVATION EQUATIONS FOR TURBULENT FLOW
- MODELING THE COMBUSTION TERMS IN THESE EQUATIONS
- MODELING THE RADIATION TERMS IN THESE EQUATIONS
- WRITING THE BOUNDARY CONDITIONS FOR A GIVEN SITUATION
- WRITING THE INITIAL CONDITIONS FOR A GIVEN SITUATION
- FINDING THE VALUE OF THE RELEVANT BASIC CONSTANTS THAT ARE RELATED TO MATERIAL PROPERTIES

THE CONSERVATION EQUATIONS

MASS

$$\underset{\text{transient term}}{\frac{\partial \rho}{\partial t}} + \underbrace{\frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y}}_{\text{convective terms}} = 0$$

x-MOMENTUM COMPONENT

$$\underset{\text{transient term}}{\rho \frac{\partial u}{\partial t}} + \underbrace{\rho u \frac{\partial u}{\partial x} + \rho v \frac{\partial u}{\partial y}}_{\text{convective terms}} = - \underset{\text{pressure change term}}{\frac{\partial p}{\partial x}} \underset{\text{buoyancy term}}{- g \rho \sin \theta} +$$

$$\underbrace{\frac{\partial}{\partial x}\left[\left(-\frac{2}{3}\mu_T\right)\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right)\right] + 2\frac{\partial}{\partial x}\left(\mu_{x_T}\frac{\partial u}{\partial x}\right) + \frac{\partial}{\partial y}\left[\mu_{y_T}\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)\right]}_{\text{viscous stress terms (turbulent)}}$$

THE CONSERVATION EQUATIONS
(2 of 3)

y-MOMENTUM COMPONENT

$$\underset{\substack{\text{transient}\\ \text{term}}}{\rho\frac{\partial v}{\partial t}} + \underbrace{\rho u \frac{\partial v}{\partial x} + \rho v \frac{\partial v}{\partial y}}_{\text{convective terms}} = \underset{\substack{\text{pressure}\\ \text{change}\\ \text{term}}}{-\frac{\partial p}{\partial y}} \underset{\substack{\text{buoyancy}\\ \text{term}}}{-\, g\rho\cos\theta}$$

$$\underbrace{+ \frac{\partial}{\partial x}\left[\mu_{x_T}\left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}\right)\right] + \frac{\partial}{\partial y}\left[\left(-\frac{2}{3}\mu_T\right)\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right)\right] + 2\frac{\partial}{\partial y}\left[\mu_{y_T}\frac{\partial v}{\partial y}\right]}_{\substack{\text{viscous stress terms}\\ \text{(turbulent)}}}$$

SPECIES

$$\underset{\substack{\text{transient}\\ \text{term}}}{\rho\frac{\partial Y_i}{\partial t}} + \underbrace{\rho u \frac{\partial Y_i}{\partial x} + \rho v \frac{\partial Y_i}{\partial y}}_{\text{convective terms}} = \underbrace{\frac{\partial}{\partial x}\left(D_{x_T}\ \rho\frac{\partial Y_i}{\partial x}\right) + \frac{\partial}{\partial y}\left(D_{y_T}\ \rho\frac{\partial Y_i}{\partial y}\right)}_{\substack{\text{diffusive terms}\\ \text{(turbulent)}}} + \underset{\substack{\text{source}\\ \text{or sink}\\ \text{term}}}{\dot{\omega}_i}$$

i = fuel, oxygen, nitrogen, water, carbon dioxide.

THE CONSERVATION EQUATIONS

(3 of 3)

ENERGY

$$\underset{\substack{\text{transient}\\ \text{term}}}{\rho C_p \frac{\partial T}{\partial t}} + \underbrace{\rho u \, C_p \frac{\partial T}{\partial x} + \rho v \, C_p \frac{\partial T}{\partial y}}_{\text{convective terms}} = \underset{\substack{\text{pressure}\\ \text{change}\\ \text{term}}}{\frac{\partial p}{\partial t}} + \underbrace{\frac{\partial}{\partial x}\left(k_{x_T} \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_{y_T} \frac{\partial T}{\partial y}\right)}_{\text{conductive terms (turbulent)}}$$

$$\underset{\text{work}}{- g\rho v} + \underset{\substack{\text{source of}\\ \text{heat due}\\ \text{to combustion}}}{\dot{Q}\rho} + \underset{\substack{\text{radiation}\\ \text{term}}}{\dot{R}_{net}}$$

STATE

$$p = \rho R T \quad \text{with} \quad R = R_u \Sigma_i \frac{Y_i}{w_i}$$

MODELING OF COMBUSTION

$$C_n H_m + \left(n + \frac{m}{4}\right) O_2 \longrightarrow n\, CO_2 + \frac{m}{2} H_2O$$

$$\dot{\omega}_F = c_1 \dot{\omega}_{O_2} \qquad \text{with} \qquad c_1 = \frac{w_F}{w_{O_2}} \frac{1}{n + \frac{m}{4}}$$

$$\dot{\omega}_{CO_2} = -c_2 \dot{\omega}_{O_2} \qquad \text{with} \qquad c_2 = \frac{w_{CO_2}}{w_{O_2}} \frac{n}{n + \frac{m}{4}}$$

$$\dot{\omega}_{H_2O} = -c_3 \dot{\omega}_{O_2} \qquad \text{with} \qquad c_3 = \frac{w_{H_2O}}{w_{O_2}} \frac{m/2}{n + \frac{m}{4}}$$

$$\dot{\omega}_{O_2} = w_{O_2} \frac{d\,[O_2]}{dt} = -k_f \frac{1}{w_F} Y_F Y_{O_2} \rho^2 \quad \text{with} \quad k_f = Ae^{-E/RT}$$

$$\dot{Q} = \frac{1}{\rho} \left(c_1 h^0{}_F - c_2 h^0{}_{CO_2} - c_3 h^0{}_{H_2O}\right)\left(-\dot{\omega}_{O_2}\right)$$

BOUNDARY CONDITIONS

WALLS (INERT)

$$u = 0 \quad , \quad v = 0$$

$$\frac{\partial Y_i}{\partial \vec{n}} = 0$$; $\vec{n}$ is the direction perpendicular to the wall

thin wall assumption

$$\delta_w \rho_w C_w \frac{\partial T_w}{\partial t} = k_g \frac{\partial T}{\partial \vec{n}} + \dot{q}_{\substack{net \\ rad}} + l \frac{\partial}{\partial \vec{s}} \left(k_{s_w} \frac{\partial T_w}{\partial \vec{s}} \right)$$; $\vec{s}$ is the direction along the wall;

$$l = \begin{cases} H \text{ if } \vec{n} = \vec{x} \\ L \text{ if } \vec{n} = \vec{y} \end{cases}$$

ENTRANCE $(x = 0, \; ; \; y_1 < y < y_2)$

$$A \bar{\rho} \bar{u} = \dot{m}_{air}$$ (forced ventilation)

$$v = 0$$

ρ, T, Y_F, Y_{O_2}, Y_{N_2}, Y_{CO_2}, Y_{H_2O} given

BOUNDARY CONDITIONS (Cont'd)

EXIT $(x = L \, ; \, y_3 < y < y_4)$

$\rho, u, v, Y_F, Y_{O_2}, Y_{N_2}, Y_{CO_2}, Y_{H_2O}$, T are found by forward extrapolation

POOL SURFACE $(y = 0 \, , \, x_1 < x < x_2)$

$$u = 0$$

$$\rho v \, Y_F - \rho D \frac{\partial Y_F}{\partial y} = \dot{M}_F$$

$$\rho v \, Y_i - \rho D \frac{\partial Y_i}{\partial y} = 0 \qquad i = O_2, N_2, CO_2, H_2O$$

$$\dot{M}_F = \alpha \, p_{atm} \left\{ e^{\frac{L_g}{R_u}\left(\frac{1}{T_b} - \frac{1}{T_l}\right)} - \frac{Y_F}{W_F} \frac{1}{\sum \frac{Y_i}{W_i}} \right\} \left(\frac{W_F}{2\pi \tilde{R} T_l} \right)^{1/2}$$

thin wall assumption

$$\delta_l \, \rho_l C_l \frac{\partial T_l}{\partial t} = k_g \frac{\partial T}{\partial y} + \dot{q}_{\substack{net \\ rad}} - \dot{M}_F L_g$$

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PRESENT AND FUTURE WORK

1) MODEL THE RADIATION TERMS
   - IN THE ENERGY EQUATION
   - IN THE BOUNDARY CONDITIONS
2) ENCODE THE EQUATIONS
   - SELECT A COMPUTATION SCHEME
   - TRANSFORM THE EQUATIONS FROM A DIFFERENTIAL TO A FINITE FORM
   - DEVELOP A COMPUTER CODE
3) ASCERTAIN THERMOPHYSICAL AND THERMOCHEMICAL CONSTANTS THAT ARE RELEVENT TO AIRCRAFT MATERIALS
4) CHARACTERIZE THE FLOW CONDITIONS IN AIRCRAFT (LEVELS OF TURBULENCE) USING AVAILABLE EXPERIMENTAL DATA